

# A Consortium For Ocean Circulation And Climate Estimation

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## LONG-TERM GOALS

To bring, in the collaborative ECCO effort together with groups at JPL and MIT, ocean state estimation from its current experimental status to a practical and quasi-operational tool for studying large-scale ocean dynamics, designing observational strategies and examining the ocean's role in climate variability.

## OBJECTIVES

We will improve the ocean general circulation models upon which assimilation is based, evaluate and improve assimilation techniques, and confront the practical problems of marshaling large data sets and carrying out routine assimilation runs.

Our central technical goal is a complete global-scale ocean state estimation over at least the 15 year period 1985-2000 at 1/4° resolution with a complete error description and regional refinements to support CLIVAR and GODAE needs. We will combine all available and anticipated large-scale data sets — including TOPEX/POSEIDON, TOGA-TAO, high-resolution VOS XBT/XCTD, profiling floats, and drifters — with the dynamics embodied in a general circulation model to estimate the time-evolving, three-dimensional physical state of the full oceanic circulation.

We will supplement the global state-estimates with high-resolution regional studies in support of CLIVAR's Basin-wide Extended Climate Studies (BECS) in the North Atlantic and the North Pacific. Global and regional results will be evaluated using available high-quality data sets and estimate covariance functions for processes and errors in data and models.

## APPROACH

Our focus is on the state estimation of the global ocean in its entirety combining together all suitable data sets. Our interest is to draw models and observations together over decades of time to arrive at a

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complete (i.e., including aspects not directly measured) dynamical description of ocean circulation, such as insights into the natures of climate-related ocean variability, major ocean transport pathways, heat and freshwater flux divergences (similar for tracer and oxygen, silica, nitrate), location and rate of ventilation, and of the ocean's response to atmospheric variability.

The ECCO activities are performed in three groups located at MIT (J. Marshall, and C. Wunsch), JPL (I. Fukumori, L.-L. Fu, T. Lee, D. Menemenlis, and V. Zlotnicki) and SIO (D. Stammer (PI), R. Davis, P. Niiler). Each institution has its own task within the entire approach as described below, covering model development, estimation activities, data preparation and scientific analyses. The ongoing ocean state estimations are based on the MIT GCM (*Marshall, et al.*, 1997) and two parallel optimization efforts: MIT and SIO use the adjoint method (Lagrange multipliers or constrained optimization method), exploiting the Tangent-linear and Adjoint Compiler (TAMC) of *Giering and Kaminski*, (1997) as described in *Marotzke et al.* (1999), while JPL's focus is primarily on a reduced state Kalman filter, e.g., *Fukumori et al.*, (1999). Those data assimilation activities can be summarized as finding a rigorous solution of the time-varying model state  $\mathbf{x}$  over time  $t$  that minimizes in a least-squares sense a sum of model-data misfits and deviations from model equations while taking into account the errors in both.

This report will focus on activities at SIO; the activities at JPL and MIT are being summarized in separate reports.

## WORK COMPLETED

At SIO, activities by D. Stammer and his group were centered around performing the global ocean state estimate on a  $2^\circ$  spatial grid over the period 1992 through 2000 using the MIT adjoint model. This run has converged and D. Stammer performed a considerable analysis of the model output in collaboration with the MIT group (C. Wunsch) with respect to its realism, and with respect to time-varying ocean circulation and transports. For that purpose, we prepared altimetric data and other WOCE data input of the optimization. Equally important many large-scale data sets were processed for a comparison of the existing ocean state with independent data. In the next experiments those fields will then be included in the optimization which include the global WOCE hydrography, the global XBT data set (including the TAO data) and the preparation of the global surface drifter data set (P. Niiler) and float fields (R. Davis).

Two papers have been submitted (*Stammer et al.*, 2001a,b) and several others are in preparation (e.g., *Lu and Stammer*, 2001; *Stammer et al.*, 2001; *The ECCO Group*, 2001).

## RESULTS

The most outstanding result of the ongoing and continuing work is that we were able to complete a first global ocean state estimation of the time-varying circulation over the 9-year time interval 1992 through 2000. Data currently employed in the synthesis include the absolute and time-varying T/P data from October 1992 through December 2000, SSH anomalies from the ERS-1 and ERS-2 satellites, monthly mean sea-surface temperature data (*Reynolds and Smith*, 1994), time-varying NCEP reanalysis fluxes of momentum, heat, freshwater, and NSCAT estimates of wind stress errors. Monthly means of the model state are required to remain within assigned bounds of the monthly

mean *Levitus et al.* (1994) climatology and a drift of the model over the 9 year period is penalized to bring the model hydrography into a stable equilibrium with surface fluxes. To bring the model into consistency with the observations, the initial potential temperature ( $\theta$ ) and salinity (S) fields are modified, as well as the surface forcing fields. Changes in those fields (often referred to as "control" terms) are determined as a best-fit (in a least-squares sense) of the model state to the observations and their uncertainties over the full data period.

We use this model-based synthesis in this paper for a first dynamical description of the time-evolving ocean circulation, its major ocean transport pathways, heat and freshwater flux divergences and of the ocean's response to atmospheric variability. We note that this approach is also a procedure to estimate surface fluxes of momentum, heat and freshwater and their uncertainties that are required to bring ocean models into consistency with ocean. The obtained solution is thus a complete description of the ocean flow fields, its transport properties and surface fluxes that all have to be consistent with each other. A full account of results of this global WOCE synthesis is given by *Stammer et al.* (2001a, b, c). Many interdisciplinary applications are already under way or have begun recently, including studies of the ocean's impact on the earth angular momentum budget (*Ponte et al.*, 2000). Results and model output are also provided on the ECCO project web site <http://www.ecco-group.org>. Only a few results can be summarized here.

The mean net surface heat flux field as it results from the optimization is displayed in the upper panel of Fig.1. Its time-mean change relative to the prior NCEP field is provided in the lower panel of the figure. Changes are on the order of  $\pm 20 \text{ W/m}^2$  and are over all consistent with prior information about the NCEP flux uncertainties. Similar changes are also obtained for wind stress and net surface freshwater fluxes.

Fig. 2 shows zonally integrated meridional heat fluxes for the global ocean. The green open circles show the zonal integrals as obtained by *Ganachaud and Wunsch* (2000). Although our estimates agree with theirs surprisingly well in the Southern Hemisphere and in the North Pacific, large discrepancies exist over the Atlantic where we estimate only about 50% of their amplitude, except at 10°N and at the southern end of the picture. However, this result is unsurprising in a 2° lateral resolution model in which the boundary currents are sluggish and diffuse, with the data unable to impose a different, sharper, spatial structure. Despite this resolution problem, the gross pattern of North Atlantic poleward heat flux is reproduced and its dependence on the closed nature of the poleward model boundaries or other model parameters has to be investigated. See *Stammer et al.* (2001b,c) for a further discussion.

## IMPACT/APPLICATION

Many interdisciplinary applications are now under way or have begun recently, including our studies which show the ocean's impact on the earth angular momentum budget and the importance of ocean state estimation for those studies (*Ponte et al.*, 2000). Other applications include simulations of tracer and carbon distribution as they began already at MIT and SIO. Moreover, the ECCO consortium will be in close contact with the recently formed NOPP node lead by L. Rothein on physical/biological modeling in the North Atlantic. The ECCO consortium is already in close collaboration with the NOPP FRONT node and the HYCOM NOPP node in terms of technology transfer and interchange of scientific results.

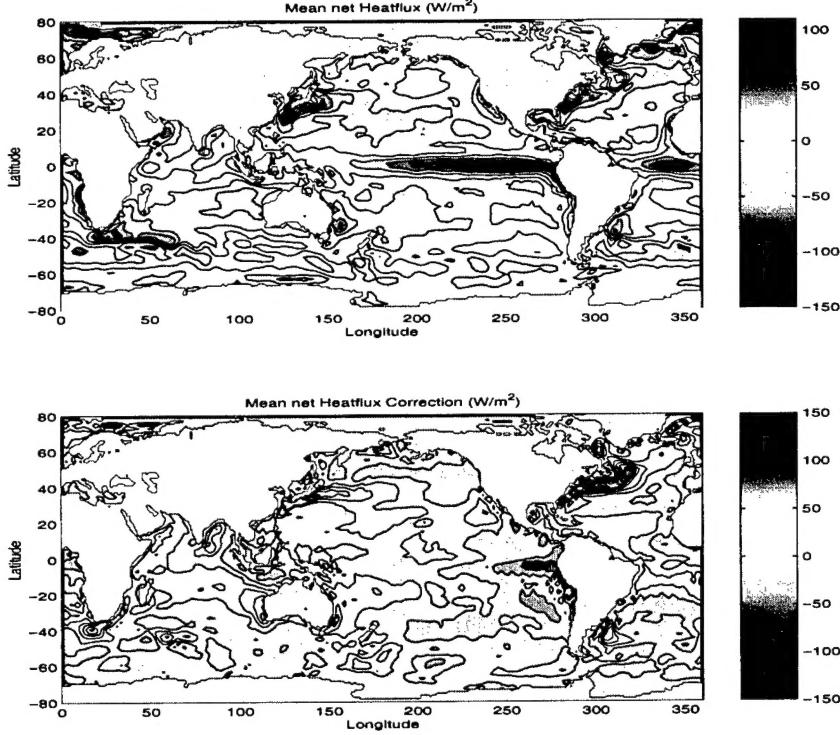


Figure 1: The mean net surface heat field as it results from the optimization is displayed in the upper panel. Its mean change relative to the prior NCEP fields is provided in the middle panel. All resulting modifications of the net NCEP heat fluxes, which are of the order of  $\pm 20 \text{ W m}^{-2}$  over large parts of the interior oceans and reach  $\pm 80 \text{ W m}^{-2}$  along the boundary currents, are consistent with our prior understanding of NCEP heat flux errors.

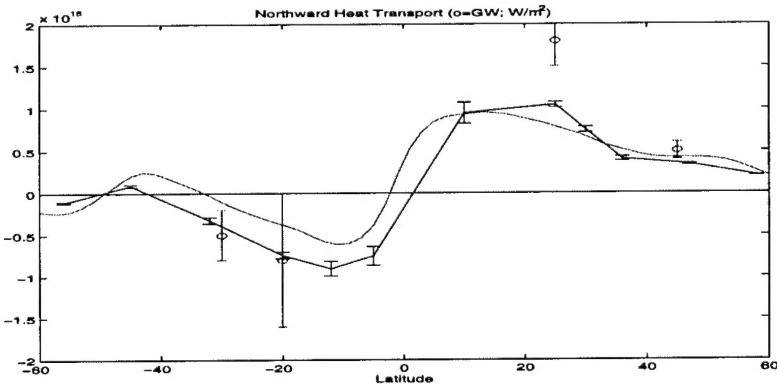


Figure 2: Integrated time-mean meridional heat transports for the global ocean estimated for various zonal sections in the model (blue curve). The blue error bars are estimated as  $\sigma/\sqrt{N}$ . The green error bars mark the standard deviation obtained from individual annual mean estimates. The red curve represents the ocean heat transport inferred from estimated surface heat fluxes.

The ECCO estimated time-varying model state and consistent surface flux fields from the entire estimation period can be accessed via the project's Live-Access-Server (LAS) <http://www.ecco-group.org/las>. And many more interactions/collaborations are expected to spin up over the next year.

## TRANSITIONS

Now ongoing computations move toward a 10-year estimate of the time-evolving ocean circulation (1992 through 2001) with  $1^{\circ}$  spatial resolution that uses all major WOCE data sets as constraints, and that has built in a complete mixed layer model (*Large et al.*, 1994) and an eddy parameterization scheme (*Gent and McWilliams*, 1990). It is intended to present this unprecedented synthesis at the final WOCE conference, end of 2002 as the next mile stone within the project. Furthermore it is anticipated that, in two to three years, the project will be able to address the US CLIVAR and GODAE related objective of depicting the time-evolving ocean state with spatial resolution up to  $1/4^{\circ}$  globally and with substantially higher resolution in nested regional approaches which are required for quantitative studies of the ocean circulation.

## RELATED PROJECTS

1 - HYCOM Consortium for Data-Assimilative Ocean Modeling: it is anticipated that the ECCO and HYCOM results will be inter compared to identify model-related agreements and uncertainties in both estimation approaches.

2 - Front Resolving Observational Network with Telemetry makes use of the models and techniques developed as part of ECCO. It is anticipated that the FRONT modeling activity will be embedded into the ECCO estimation results.

3 - NOPP Virtual Ocean Data Hub: this activity is essential for setting up the ECCO live access server.

4 - Rothstein et al NOPP Node this recently funded NOPP activity will heavily rely on our estimated physical states.

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